

Anderson Sweeney Williams Camm Cochran Fry Ohlmann

# An Introduction to Management Science

Quantitative Approaches to Decision Making



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Quantitative Approaches to Decision Making

*Fifteenth Edition*



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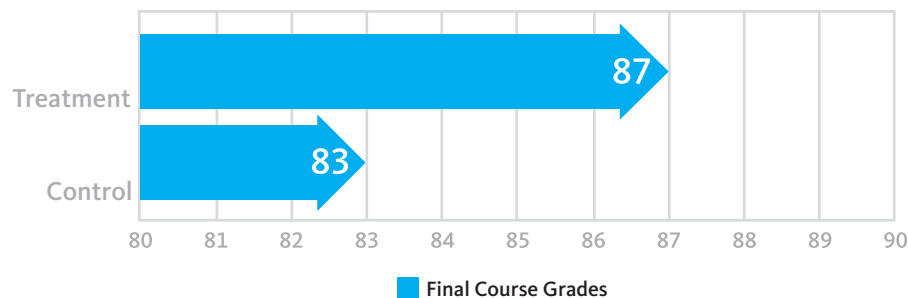
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***An Introduction to Management Science:  
Quantitative Approaches to Decision  
Making, Fifteenth Edition***

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Thomas A. Williams, Jeffrey D. Camm,  
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*Dedication*

*To My Parents  
Ray and Ilene Anderson  
DRA*

*To My Parents  
James and Gladys Sweeney  
DJS*

*To My Parents  
Phil and Ann Williams  
TAW*

*To My Parents  
Randall and Jeannine Camm  
JDC*

*To My Wife  
Teresa  
JJC*

*To My Parents  
Mike and Cynthia Fry  
MJF*

*To My Parents  
Willis and Phyllis Ohlmann  
JWO*





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# Preface

We are very excited to publish the fifteenth edition of a text that has been a leader in the field for over 25 years. The purpose of this fifteenth edition, as with previous editions, is to provide undergraduate and graduate students with a sound conceptual understanding of the role that management science plays in the decision-making process. The text describes many of the applications where management science is used successfully. Former users of this text have told us that the applications we describe have led them to find new ways to use management science in their organizations.

*An Introduction to Management Science: Quantitative Approaches to Decision Making, 15e* is applications oriented and continues to use the problem-scenario approach that is a hallmark of every edition of the text. Using the problem scenario approach, we describe a problem in conjunction with the management science model being introduced. The model is then solved to generate a solution and recommendation to management. We have found that this approach helps to motivate the student by demonstrating not only how the procedure works, but also how it contributes to the decision-making process.

From the first edition we have been committed to the challenge of writing a textbook that would help make the mathematical and technical concepts of management science understandable and useful to students of business and economics. Judging from the responses from our teaching colleagues and thousands of students, we have successfully met the challenge. Indeed, it is the helpful comments and suggestions of many loyal users that have been a major reason why the text is so successful.

Throughout the text we have utilized generally accepted notation for the topic being covered so those students who pursue study beyond the level of this text should be comfortable reading more advanced material. To assist in further study, a references and bibliography section is included at the back of the book.

## CHANGES IN THE FIFTEENTH EDITION

We are very excited about the changes in the fifteenth edition of Management Science and want to explain them and why they were made. Many changes have been made throughout the text in response to suggestions from instructors and students. While we cannot list all these changes, we highlight the more significant revisions.

### Updated Chapter 12: Simulation

The most substantial content change in this latest edition involves the coverage of simulation. We maintain an intuitive introduction by continuing to use the concepts of best-, worst-, and base-case scenarios, but we have added a more elaborate treatment of uncertainty by using Microsoft Excel to develop spreadsheet simulation models. Within the chapter, we explain how to construct a spreadsheet simulation model using only native Excel functionality. The chapter also includes two new appendices. The first appendix describes several probability distributions commonly used in simulation and how to generate values from these distributions using native Excel commands. In the second appendix, we introduce an Excel add-in, Analytic Solver, which facilitates the construction and analysis of spreadsheet simulation models. Nine new problems are introduced, and several others have been updated to reflect the new simulation coverage.

## Other Content Changes

A variety of other changes have been made throughout the text. Appendices 4.1 and 7.1 have been updated to reflect changes to Solver in Microsoft Excel 2016. An appendix has been added to Chapter 15 that discusses the Forecast Tool in Microsoft Excel 2016. In addition to updating Appendix A for Microsoft Excel 2016, we have added a section on conducting a what-if analysis using Data Tables and Goal Seek.

## Management Science in Action

The Management Science in Action vignettes describe how the material covered in a chapter is used in practice. Some of these are provided by practitioners. Others are based on articles from publications such as *Interfaces* and *OR/MS Today*. We updated the text with nine new Management Science in Action vignettes in this edition.

## Cases and Problems

The quality of the problems and case problems is an important feature of the text. In this edition we have updated over 15 problems and added 3 new case problems.

## COMPUTER SOFTWARE INTEGRATION

To make it easy for new users of Excel Solver or LINGO, we provide both Excel and LINGO files with the model formulation for every optimization problem that appears in the body of the text. The model files are well-documented and should make it easy for the user to understand the model formulation. The text is updated for Microsoft Excel 2016, but Excel 2010 and later versions allow all problems to be solved using the standard version of Excel Solver. For LINGO users, the text has been updated for LINGO 16.0.

## FEATURES AND PEDAGOGY

We have continued many of the features that appeared in previous editions. Some of the important ones are noted here.

### Annotations

Annotations that highlight key points and provide additional insights for the student are a continuing feature of this edition. These annotations, which appear in the margins, are designed to provide emphasis and enhance understanding of the terms and concepts being presented in the text.

### Notes and Comments

At the end of many sections, we provide Notes and Comments designed to give the student additional insights about the methodology and its application. Notes and Comments include warnings about or limitations of the methodology, recommendations for application, brief descriptions of additional technical considerations, and other matters.



## Self-Test Exercises

Certain exercises are identified as self-test exercises. Completely worked-out solutions for those exercises are provided in an appendix at the end of the text. Students can attempt the self-test exercises and immediately check the solution to evaluate their understanding of the concepts presented in the chapter.

## ANCILLARY TEACHING AND LEARNING MATERIALS

### For Students

Print and online resources are available to help the student work more efficiently.

- **LINGO.** A link to download an educational version of the LINGO software is available on the student website at [www.cengagebrain.com](http://www.cengagebrain.com).
- **Analytic Solver.** If using Analytic Solver with this text, you can receive the latest Analytic Solver license at Frontline Systems—[academic@solver.com](mailto:academic@solver.com) or 775-831-0300.

### For Instructors

Instructor support materials are available to adopters from the Cengage Learning customer service line at 800-423-0563 or through [www.cengage.com](http://www.cengage.com). Instructor resources are available on the Instructor Companion Site, which can be found and accessed at [login.cengage.com](http://login.cengage.com), including:

- **Solutions Manual.** The Solutions Manual, prepared by the authors, includes solutions for all problems in the text.
- **Solutions to Case Problems.** These are also prepared by the authors and contain solutions to all case problems presented in the text.
- **PowerPoint Presentation Slides.** The presentation slides contain a teaching outline that incorporates figures to complement instructor lectures.
- **Test Bank.** Cengage Learning Testing Powered by Cognero is a flexible, online system that allows you to:
  - author, edit, and manage test bank content from multiple Cengage Learning solutions,
  - create multiple test versions in an instant,
  - deliver tests from your LMS, your classroom or wherever you want. The Test Bank is also available in Microsoft Word.

### CengageNOWv2

CengageNOWv2 is a powerful course management and online homework tool that provides robust instructor control and customization to optimize the learning experience and meet desired outcomes. CengageNOWv2 features author-written homework from the textbook, integrated eBook, assessment options, and course management tools, including gradebook.

For more information about instructor resources, please contact your Cengage Learning Consultant.

## ACKNOWLEDGMENTS

We owe a debt to many of our colleagues and friends whose names appear below for their helpful comments and suggestions during the development of this and previous editions. Our associates from organizations who supplied several of the Management Science in Action vignettes make a major contribution to the text. These individuals are cited in a credit line associated with each vignette.

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*Thomas A. Williams*  
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# An Introduction to Management Science

Quantitative Approaches to Decision Making

*Fifteenth Edition*





# CHAPTER 1

## Introduction

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Management science, an approach to decision making based on the scientific method, makes extensive use of quantitative analysis. A variety of names exist for the body of knowledge involving quantitative approaches to decision making; in addition to management science, two other widely known and accepted names are operations research and decision science. Today, many use the terms *management science*, *operations research*, and *decision science* interchangeably.

The scientific management revolution of the early 1900s, initiated by Frederic W. Taylor, provided the foundation for the use of quantitative methods in management. But modern management science research is generally considered to have originated during the World War II period, when teams were formed to deal with strategic and tactical problems faced by the military. These teams, which often consisted of people with diverse specialties (e.g., mathematicians, engineers, and behavioral scientists), were joined together to solve a common problem by utilizing the scientific method. After the war, many of these team members continued their research in the field of management science.

Two developments that occurred during the post–World War II period led to the growth and use of management science in nonmilitary applications. First, continued research resulted in numerous methodological developments. Probably the most significant development was the discovery by George Dantzig, in 1947, of the simplex method for solving linear programming problems. At the same time these methodological developments were taking place, digital computers prompted a virtual explosion in computing power. Computers enabled practitioners to use the methodological advances to solve a large variety of problems. The computer technology explosion continues; smart phones, tablets, and other mobile-computing devices can now be used to solve problems larger than those solved on mainframe computers in the 1990s.

More recently, the explosive growth of data from sources such as smart phones and other personal-electronic devices provide access to much more data today than ever before. Additionally, the Internet allows for easy sharing and storage of data, providing extensive access to a variety of users to the necessary inputs to management-science models.

As stated in the Preface, the purpose of the text is to provide students with a sound conceptual understanding of the role that management science plays in the decision-making process. We also said that the text is application oriented. To reinforce the applications nature of the text and provide a better understanding of the variety of applications in which management science has been used successfully, Management Science in Action articles are presented throughout the text. Each Management Science in Action article summarizes an application of management science in practice. The first Management Science in Action in this chapter, Revenue Management at AT&T Park, describes one of the most important applications of management science in the sports and entertainment industry.

## MANAGEMENT SCIENCE IN ACTION

### REVENUE MANAGEMENT AT AT&T PARK\*

Imagine the difficult position Russ Stanley, Vice President of Ticket Services for the San Francisco Giants, found himself facing late in the 2010 baseball season. Prior to the season, his organization adopted a dynamic approach to pricing its tickets similar to the model successfully pioneered by Thomas M. Cook and his operations research group at American Airlines. Stanley desperately wanted the Giants to clinch a playoff berth, but he didn't want the team to do so *too quickly*.

When dynamically pricing a good or service, an organization regularly reviews supply and demand

of the product and uses operations research to determine if the price should be changed to reflect these conditions. As the scheduled takeoff date for a flight nears, the cost of a ticket increases if seats for the flight are relatively scarce. On the other hand, the airline discounts tickets for an approaching flight with relatively few ticketed passengers. Through the use of optimization to dynamically set ticket prices, American Airlines generates nearly \$1 billion annually in incremental revenue.

The management team of the San Francisco Giants recognized similarities between their primary

product (tickets to home games) and the primary product sold by airlines (tickets for flights) and adopted a similar revenue management system. If a particular Giants' game is appealing to fans, tickets sell quickly and demand far exceeds supply as the date of the game approaches; under these conditions fans will be willing to pay more and the Giants charge a premium for the ticket. Similarly, tickets for less attractive games are discounted to reflect relatively low demand by fans. This is why Stanley found himself in a quandary at the end of the 2010 baseball season. The Giants were in the middle of a tight pennant race with the San Diego Padres that effectively increased demand for tickets to Giants' games, and the team was actually scheduled to play the Padres in San Francisco for the last three games of the season. While Stanley certainly wanted his club to win its division and reach the Major League Baseball playoffs, he also recognized that his team's revenues would be greatly enhanced if it didn't qualify for the playoffs until the last day of the season. "I guess financially it is better to go all the way down to the last game," Stanley said in a late season interview.

"Our hearts are in our stomachs; we're pacing watching these games."

Does revenue management and operations research work? Today, virtually every airline uses some sort of revenue-management system, and the cruise, hotel, and car rental industries also now apply revenue-management methods. As for the Giants, Stanley said dynamic pricing provided a 7% to 8% increase in revenue per seat for Giants' home games during the 2010 season. Coincidentally, the Giants did win the National League West division on the last day of the season and ultimately won the World Series. Several professional sports franchises are now looking to the Giants' example and considering implementation of similar dynamic ticket-pricing systems.

\*Based on Peter Horner, "The Sabre Story," *ORMS Today* (June 2000); Ken Belson, "Baseball Tickets Too Much? Check Back Tomorrow," *New York Times.com* (May 18, 2009); and Rob Gloster, "Giants Quadruple Price of Cheap Seats as Playoffs Drive Demand," *Bloomberg Business-week* (September 30, 2010).

## 1.1 PROBLEM SOLVING AND DECISION MAKING

**Problem solving** can be defined as the process of identifying a difference between the actual and the desired state of affairs and then taking action to resolve the difference. For problems important enough to justify the time and effort of careful analysis, the problem-solving process involves the following seven steps:

1. Identify and define the problem.
2. Determine the set of alternative solutions.
3. Determine the criterion or criteria that will be used to evaluate the alternatives.
4. Evaluate the alternatives.
5. Choose an alternative.
6. Implement the selected alternative.
7. Evaluate the results to determine whether a satisfactory solution has been obtained.

**Decision making** is the term generally associated with the first five steps of the problem-solving process. Thus, the first step of decision making is to identify and define the problem. Decision making ends with the choosing of an alternative, which is the act of making the decision.

Let us consider the following example of the decision-making process. For the moment assume that you are currently unemployed and that you would like a position that will lead to a satisfying career. Suppose that your job search has resulted in offers from companies in Rochester, New York; Dallas, Texas; Greensboro, North Carolina; and Pittsburgh, Pennsylvania. Thus, the alternatives for your decision problem can be stated as follows:

1. Accept the position in Rochester.
2. Accept the position in Dallas.
3. Accept the position in Greensboro.
4. Accept the position in Pittsburgh.

The next step of the problem-solving process involves determining the criteria that will be used to evaluate the four alternatives. Obviously, the starting salary is a factor of some

**TABLE 1.1** DATA FOR THE JOB EVALUATION DECISION-MAKING PROBLEM

Alternative	Starting Salary	Potential for Advancement	Job Location
1. Rochester	\$48,500	Average	Average
2. Dallas	\$46,000	Excellent	Good
3. Greensboro	\$46,000	Good	Excellent
4. Pittsburgh	\$47,000	Average	Good

importance. If salary were the only criterion of importance to you, the alternative selected as “best” would be the one with the highest starting salary. Problems in which the objective is to find the best solution with respect to one criterion are referred to as **single-criterion decision problems**.

Suppose that you also conclude that the potential for advancement and the location of the job are two other criteria of major importance. Thus, the three criteria in your decision problem are starting salary, potential for advancement, and location. Problems that involve more than one criterion are referred to as **multicriteria decision problems**.

The next step of the decision-making process is to evaluate each of the alternatives with respect to each criterion. For example, evaluating each alternative relative to the starting salary criterion is done simply by recording the starting salary for each job alternative. Evaluating each alternative with respect to the potential for advancement and the location of the job is more difficult to do, however, because these evaluations are based primarily on subjective factors that are often difficult to quantify. Suppose for now that you decide to measure potential for advancement and job location by rating each of these criteria as poor, fair, average, good, or excellent. The data that you compile are shown in Table 1.1.

You are now ready to make a choice from the available alternatives. What makes this choice phase so difficult is that the criteria are probably not all equally important, and no one alternative is “best” with regard to all criteria. Although we will present a method for dealing with situations like this one later in the text, for now let us suppose that after a careful evaluation of the data in Table 1.1, you decide to select alternative 3; alternative 3 is thus referred to as the **decision**.

At this point in time, the decision-making process is complete. In summary, we see that this process involves five steps:

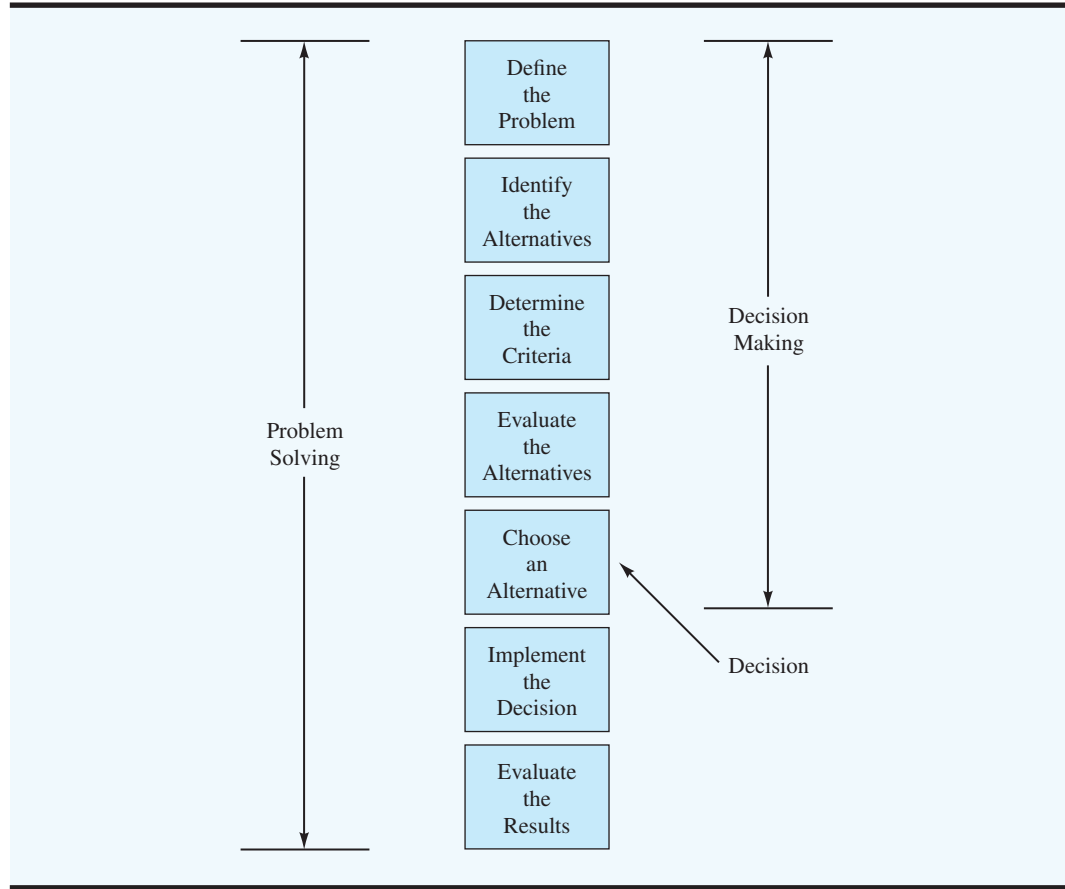
1. Define the problem.
2. Identify the alternatives.
3. Determine the criteria.
4. Evaluate the alternatives.
5. Choose an alternative.

Note that missing from this list are the last two steps in the problem-solving process: implementing the selected alternative and evaluating the results to determine whether a satisfactory solution has been obtained. This omission is not meant to diminish the importance of each of these activities, but to emphasize the more limited scope of the term *decision making* as compared to the term *problem solving*. Figure 1.1 summarizes the relationship between these two concepts.

## 1.2 QUANTITATIVE ANALYSIS AND DECISION MAKING

Consider the flowchart presented in Figure 1.2. Note that it combines the first three steps of the decision-making process under the heading “Structuring the Problem” and the latter two steps under the heading “Analyzing the Problem.” Let us now consider in greater detail how to carry out the set of activities that make up the decision-making process.

**FIGURE 1.1** THE RELATIONSHIP BETWEEN PROBLEM SOLVING AND DECISION MAKING



**FIGURE 1.2** AN ALTERNATE CLASSIFICATION OF THE DECISION-MAKING PROCESS

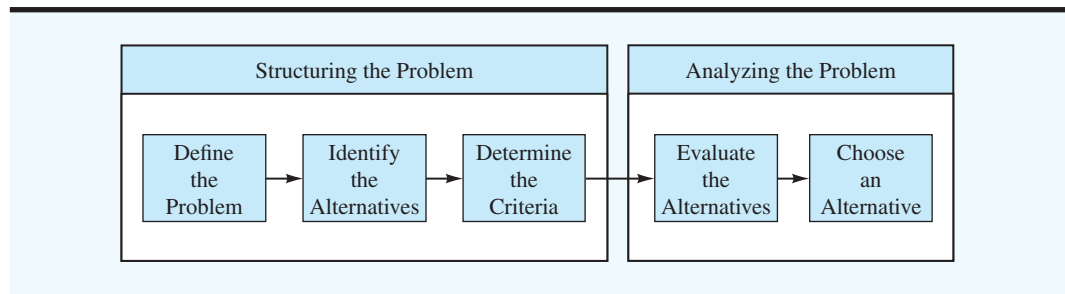
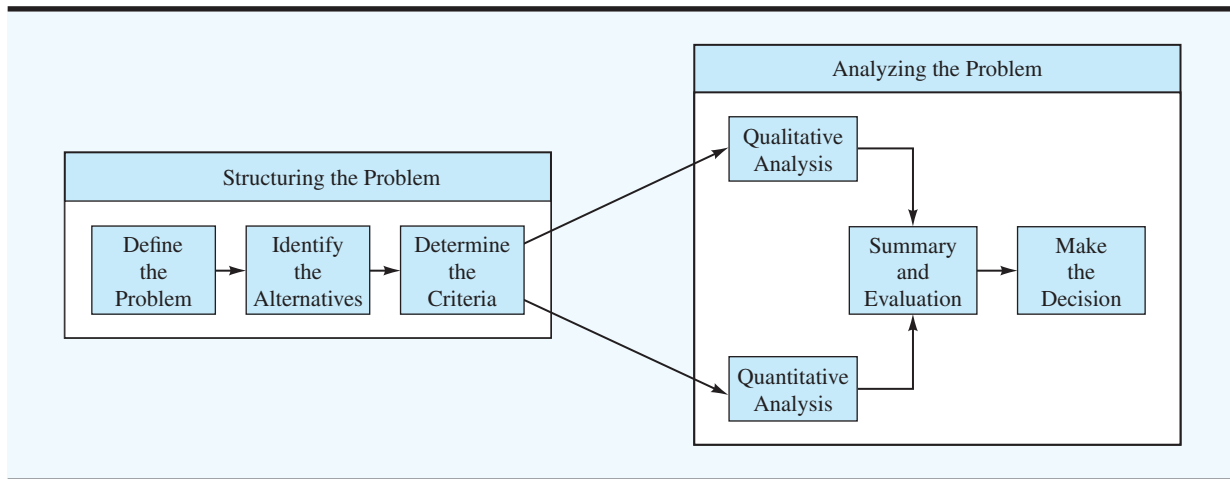


Figure 1.3 shows that the analysis phase of the decision-making process may take two basic forms: qualitative and quantitative. Qualitative analysis is based primarily on the manager’s judgment and experience; it includes the manager’s intuitive “feel” for the problem and is more an art than a science. If the manager has had experience with similar problems or if the problem is relatively simple, heavy emphasis may be placed upon a qualitative analysis. However, if the manager has had little experience with similar problems, or if the problem is sufficiently complex, then a quantitative analysis of the problem can be an especially important consideration in the manager’s final decision.

When using the quantitative approach, an analyst will concentrate on the quantitative facts or data associated with the problem and develop mathematical expressions that

**FIGURE 1.3** THE ROLE OF QUALITATIVE AND QUANTITATIVE ANALYSIS

describe the objectives, constraints, and other relationships that exist in the problem. Then, by using one or more quantitative methods, the analyst will make a recommendation based on the quantitative aspects of the problem.

Although skills in the qualitative approach are inherent in the manager and usually increase with experience, the skills of the quantitative approach can be learned only by studying the assumptions and methods of management science. A manager can increase decision-making effectiveness by learning more about quantitative methodology and by better understanding its contribution to the decision-making process. A manager who is knowledgeable in quantitative decision-making procedures is in a much better position to compare and evaluate the qualitative and quantitative sources of recommendations and ultimately to combine the two sources in order to make the best possible decision.

The box in Figure 1.3 entitled “Quantitative Analysis” encompasses most of the subject matter of this text. We will consider a managerial problem, introduce the appropriate quantitative methodology, and then develop the recommended decision.

In closing this section, let us briefly state some of the reasons why a quantitative approach might be used in the decision-making process:

1. The problem is complex, and the manager cannot develop a good solution without the aid of quantitative analysis.
2. The problem is especially important (e.g., a great deal of money is involved), and the manager desires a thorough analysis before attempting to make a decision.
3. The problem is new, and the manager has no previous experience from which to draw.
4. The problem is repetitive, and the manager saves time and effort by relying on quantitative procedures to make routine decision recommendations.

*Try Problem 4 to test your understanding of why quantitative approaches might be needed in a particular problem.*

### 1.3 QUANTITATIVE ANALYSIS

From Figure 1.3, we see that quantitative analysis begins once the problem has been structured. It usually takes imagination, teamwork, and considerable effort to transform a rather general problem description into a well-defined problem that can be approached via quantitative analysis. The more the analyst is involved in the process of structuring the problem, the more likely the ensuing quantitative analysis will make an important contribution to the decision-making process.

To successfully apply quantitative analysis to decision making, the management scientist must work closely with the manager or user of the results. When both the management scientist and the manager agree that the problem has been adequately structured, work can begin on developing a model to represent the problem mathematically. Solution procedures

can then be employed to find the best solution for the model. This best solution for the model then becomes a recommendation to the decision maker. The process of developing and solving models is the essence of the quantitative analysis process.

## Model Development

**Models** are representations of real objects or situations and can be presented in various forms. For example, a scale model of an airplane is a representation of a real airplane. Similarly, a child's toy truck is a model of a real truck. The model airplane and toy truck are examples of models that are physical replicas of real objects. In modeling terminology, physical replicas are referred to as **iconic models**.

A second classification includes models that are physical in form but do not have the same physical appearance as the object being modeled. Such models are referred to as **analog models**. The speedometer of an automobile is an analog model; the position of the needle on the dial represents the speed of the automobile. A thermometer is another analog model representing temperature.

A third classification of models—the type we will primarily be studying—includes representations of a problem by a system of symbols and mathematical relationships or expressions. Such models are referred to as **mathematical models** and are a critical part of any quantitative approach to decision making. For example, the total profit from the sale of a product can be determined by multiplying the profit per unit by the quantity sold. If we let  $x$  represent the number of units sold and  $P$  the total profit, then, with a profit of \$10 per unit, the following mathematical model defines the total profit earned by selling  $x$  units:

$$P = 10x \quad (1.1)$$

The purpose, or value, of any model is that it enables us to make inferences about the real situation by studying and analyzing the model. For example, an airplane designer might test an iconic model of a new airplane in a wind tunnel to learn about the potential flying characteristics of the full-size airplane. Similarly, a mathematical model may be used to make inferences about how much profit will be earned if a specified quantity of a particular product is sold. According to the mathematical model of equation (1.1), we would expect selling three units of the product ( $x = 3$ ) would provide a profit of  $P = 10(3) = \$30$ .

In general, experimenting with models requires less time and is less expensive than experimenting with the real object or situation. A model airplane is certainly quicker and less expensive to build and study than the full-size airplane. Similarly, the mathematical model in equation (1.1) allows a quick identification of profit expectations without actually requiring the manager to produce and sell  $x$  units. Models also have the advantage of reducing the risk associated with experimenting with the real situation. In particular, bad designs or bad decisions that cause the model airplane to crash or a mathematical model to project a \$10,000 loss can be avoided in the real situation.

The value of model-based conclusions and decisions is dependent on how well the model represents the real situation. The more closely the model airplane represents the real airplane, the more accurate the conclusions and predictions will be. Similarly, the more closely the mathematical model represents the company's true profit–volume relationship, the more accurate the profit projections will be.

Because this text deals with quantitative analysis based on mathematical models, let us look more closely at the mathematical modeling process. When initially considering a managerial problem, we usually find that the problem definition phase leads to a specific objective, such as maximization of profit or minimization of cost, and possibly a set of restrictions or **constraints**, such as production capacities. The success of the mathematical model and quantitative approach will depend heavily on how accurately the objective and constraints can be expressed in terms of mathematical equations or relationships.

A mathematical expression that describes the problem's objective is referred to as the **objective function**. For example, the profit equation  $P = 10x$  would be an objective function

*Herbert A. Simon, a Nobel Prize winner in economics and an expert in decision making, said that a mathematical model does not have to be exact; it just has to be close enough to provide better results than can be obtained by common sense.*

for a firm attempting to maximize profit. A production capacity constraint would be necessary if, for instance, 5 hours are required to produce each unit and only 40 hours of production time are available per week. Let  $x$  indicate the number of units produced each week. The production time constraint is given by

$$5x \leq 40 \quad (1.2)$$

The value of  $5x$  is the total time required to produce  $x$  units; the symbol  $\leq$  indicates that the production time required must be less than or equal to the 40 hours available.

The decision problem or question is the following: How many units of the product should be scheduled each week to maximize profit? A complete mathematical model for this simple production problem is

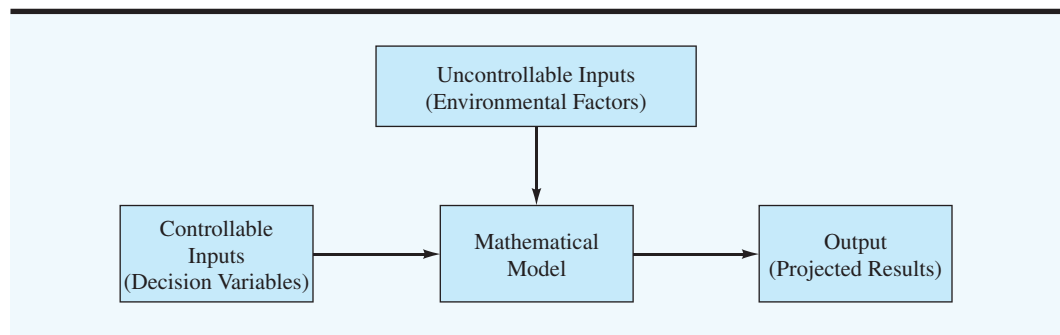
$$\begin{array}{ll} \text{Maximize} & P = 10x \quad \text{objective function} \\ \text{subject to (s.t.)} & \\ & \left. \begin{array}{l} 5x \leq 40 \\ x \geq 0 \end{array} \right\} \text{constraints} \end{array}$$

The  $x \geq 0$  constraint requires the production quantity  $x$  to be greater than or equal to zero, which simply recognizes the fact that it is not possible to manufacture a negative number of units. The optimal solution to this model can be easily calculated and is given by  $x = 8$ , with an associated profit of \$80. This model is an example of a linear programming model. In subsequent chapters we will discuss more complicated mathematical models and learn how to solve them in situations where the answers are not nearly so obvious.

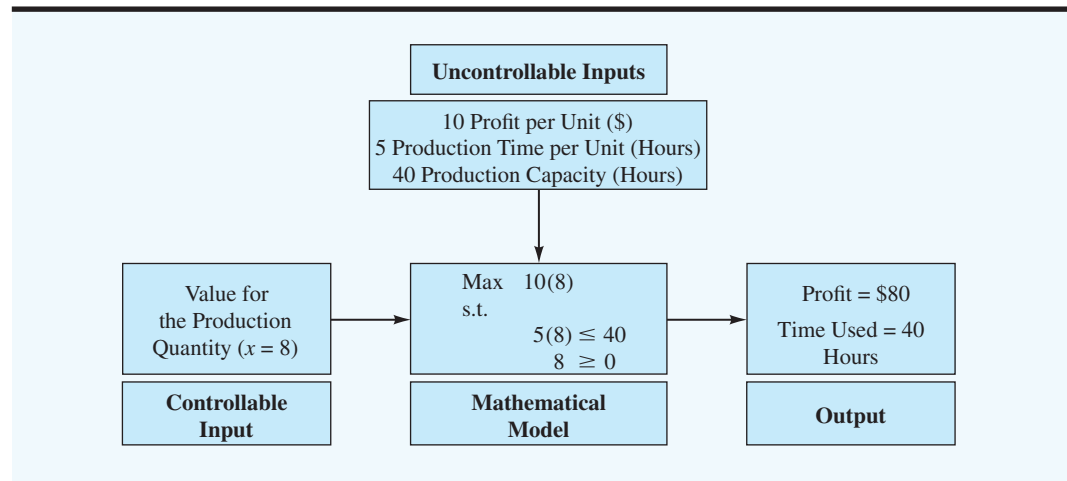
In the preceding mathematical model, the profit per unit (\$10), the production time per unit (5 hours), and the production capacity (40 hours) are environmental factors that are not under the control of the manager or decision maker. Such environmental factors, which can affect both the objective function and the constraints, are referred to as **uncontrollable inputs** to the model. Inputs that are completely controlled or determined by the decision maker are referred to as **controllable inputs** to the model. In the example given, the production quantity  $x$  is the controllable input to the model. Controllable inputs are the decision alternatives specified by the manager and thus are also referred to as the **decision variables** of the model.

Once all controllable and uncontrollable inputs are specified, the objective function and constraints can be evaluated and the output of the model determined. In this sense, the output of the model is simply the projection of what would happen if those particular environmental factors and decisions occurred in the real situation. A flowchart of how controllable and uncontrollable inputs are transformed by the mathematical model into output is shown in Figure 1.4. A similar flowchart showing the specific details of the production model is shown in Figure 1.5.

**FIGURE 1.4** FLOWCHART OF THE PROCESS OF TRANSFORMING MODEL INPUTS INTO OUTPUT





**FIGURE 1.5** FLOWCHART FOR THE PRODUCTION MODEL

As stated earlier, the uncontrollable inputs are those the decision maker cannot influence. The specific controllable and uncontrollable inputs of a model depend on the particular problem or decision-making situation. In the production problem, the production time available (40) is an uncontrollable input. However, if it were possible to hire more employees or use overtime, the number of hours of production time would become a controllable input and therefore a decision variable in the model.

Uncontrollable inputs can either be known exactly or be uncertain and subject to variation. If all uncontrollable inputs to a model are known and cannot vary, the model is referred to as a **deterministic model**. Corporate income tax rates are not under the influence of the manager and thus constitute an uncontrollable input in many decision models. Because these rates are known and fixed (at least in the short run), a mathematical model with corporate income tax rates as the only uncontrollable input would be a deterministic model. The distinguishing feature of a deterministic model is that the uncontrollable input values are known in advance.

If any of the uncontrollable inputs are uncertain to the decision maker, the model is referred to as a **stochastic** or **probabilistic model**. An uncontrollable input to many production planning models is demand for the product. A mathematical model that treats future demand—which may be any of a range of values—with uncertainty would be called a stochastic model. In the production model, the number of hours of production time required per unit, the total hours available, and the unit profit were all uncontrollable inputs. Because the uncontrollable inputs were all known to take on fixed values, the model was deterministic. If, however, the number of hours of production time per unit could vary from 3 to 6 hours depending on the quality of the raw material, the model would be stochastic. The distinguishing feature of a stochastic model is that the value of the output cannot be determined even if the value of the controllable input is known because the specific values of the uncontrollable inputs are unknown. In this respect, stochastic models are often more difficult to analyze.

## Data Preparation

Another step in the quantitative analysis of a problem is the preparation of the data required by the model. Data in this sense refer to the values of the uncontrollable inputs to the model. All uncontrollable inputs or data must be specified before we can analyze the model and recommend a decision or solution for the problem.

In the production model, the values of the uncontrollable inputs or data were \$10 per unit for profit, 5 hours per unit for production time, and 40 hours for production capacity. In the development of the model, these data values were known and incorporated into the model as